DOE/NASA 0002-80/2
NASA CR-159609

MOD-2 WIND TURBINE SYSTEM CONCEPT AND PRELIMINARY DESIGN REPORT

VOLUME I EXECUTIVE SUMMARY

Boeing Engineering and Construction
(A Division of The Boeing Company)
Seattle, Washington

July 1979

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Cleveland, Ohio 44135
Under Contract DEN 3-2

for
U.S. DEPARTMENT OF ENERGY
Energy Technology
Distributed Solar Technology Division
Washington, D.C. 20545
Under Interagency Agreement DE-AI01-793T 20305

NOTICE

DOE/NASA/0002-80/2
NASA CR-159609

MOD-2 WIND TURBINE SYSTEM CONCEPT AND PRELIMINARY DESIGN REPORT

Volume I: Executive Summary

Boeing Engineering & Construction Company
(A Division of The Boeing Company)
Seattle, Washington

July 1979

Prepared for
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135
Under Contract DEN 3-2

for
U. S. DEPARTMENT OF ENERGY
Energy Technology
Distributed Solar Technology Division
Washington, D. C. 20545
Under Interagency Agreement DE-AI01-79ET20305

TABLE OF CONTENTS

1.0 INTRODUCTION

This report, Volume I, is the Executive Summary of work performed by Boeing Engineering and Construction under NASA Contract DEN3-2, Task II, Analysis and Design Phases of the MOD-2 wind turbine project. Volume II of this documentation is the detailed report of this activity.

Contract DEN3-2, the MOD-2 WTS project, is a continuation of the United States Department of Energy programs to develop and achieve early commercialization of wind energy. The MOD-2 project and its predecessors MOD-0, MOD-0A and MOD-1 are the current DOE programs under the technical management of the NASA-Lewis Research Center.

The MOD-2 wind turbine system is design optimized for commercial production rates which, in multi-unit installations, will be integrated into a utility power grid and achieve a cost of electricity at less than 4¢ per kilowatt hour.

2.0 DESIGN APPROACH

The MOD-2 configuration evolved from extensive trade studies and sensitivity studies coupled with inputs from NASA, several utilities, and with the results of a Failure Modes and Effects Analysis (FMEA). The resulting system is optimized for a minimum cost of electricity while maintaining compatibility with existing utility networks and while meeting safety requirements. A system life of 30 years with low annual operations and maintenance costs as well as low initial costs were coupled with performance optimization to establish the design which achieves the COE goal of less than 4¢ per KWH. The design approach is illustrated in Figure 2-1.

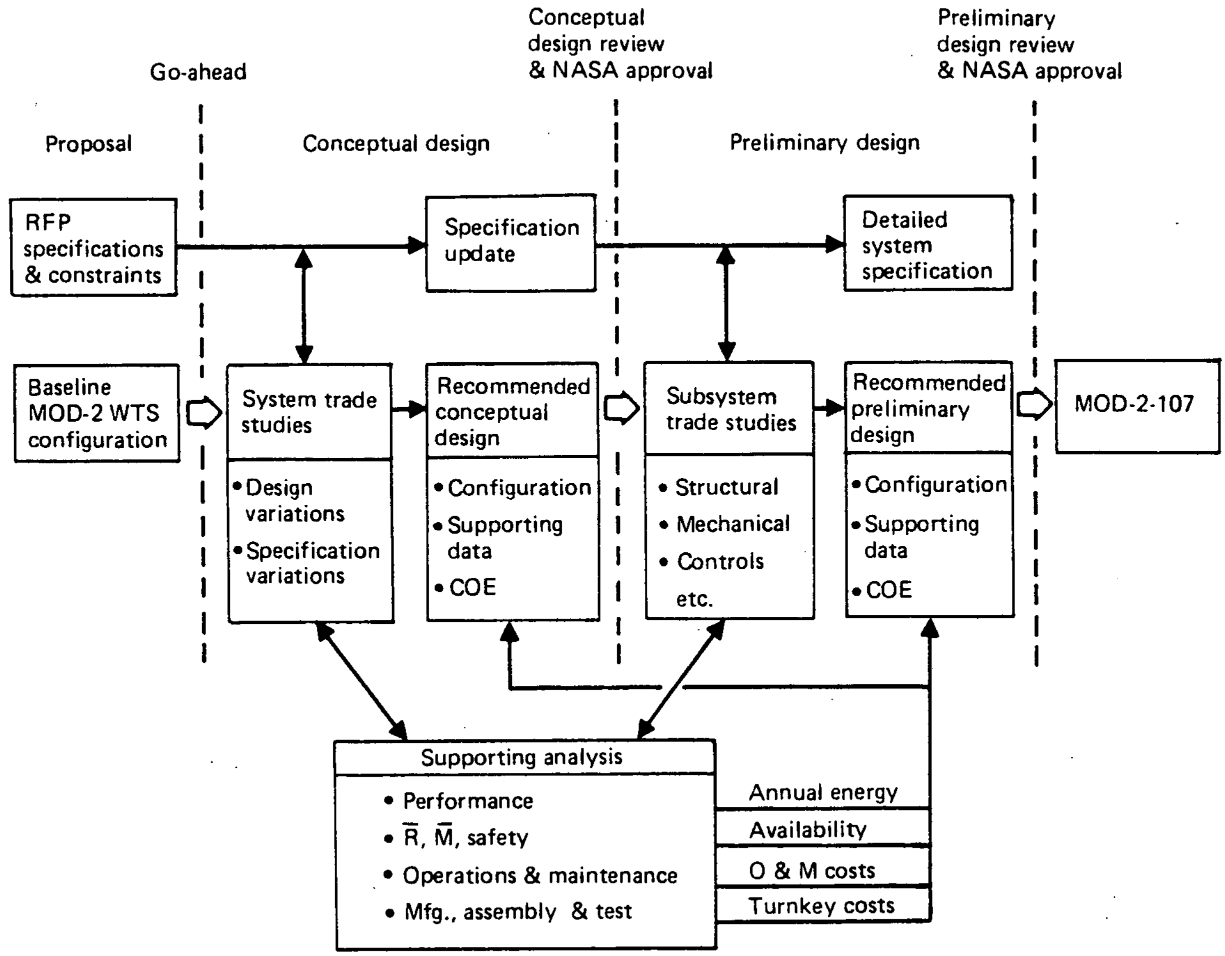


Figure 2-1. MOD-2 Wind Turbine Design Approach

3.0 SYSTEM DESCRIPTION

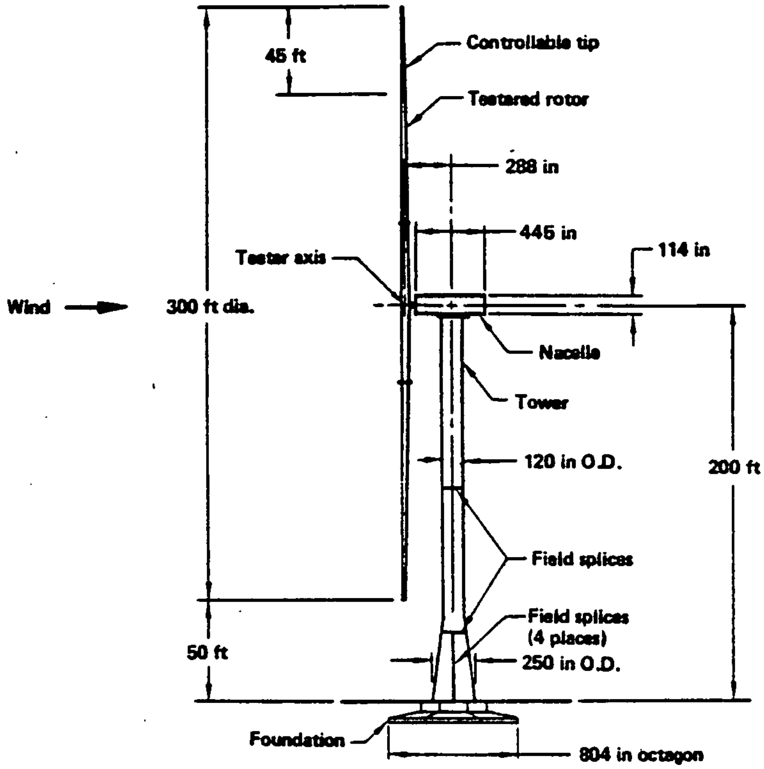
The following sub-paragraphs describe the wind turbine system (MOD-2-107) which evolved from the optimization studies during this Task II, Analysis and Design Phase.

3.1 GENERAL ARRANGEMENT AND CHARACTERISTICS

The general arrangement and characteristics of the current WTS configuration are shown in Figure 3-1. It is designed for operation at sites where the annual average wind speed is 14 mph measured at 30 feet (20 mph @ hub height). The system generates electricity when the wind speed at hub height (200 feet) exceeds 14 mph. At 27.5 mph and higher (at hub height), the system produces the rated power of 2500 kW. Above 45 mph (at hub height), the system is shut down to avoid high operating load conditions. The annual energy output at a site with a 14 mph average wind speed is nearly 10 million kWh. This energy output combined with an estimated 100th production unit turnkey cost of $1,720,000 (in 1977 dollars) results in a predicted cost of electricity of 3.3¢/kWh at the bus bar. During operation, the wind turbine is tied to the utilities power grid through standard transmission lines.

The WTS is a horizontal axis machine utilizing a 300 foot diameter partial span control, upwind rotor. The rotor's center of rotation is 200 feet above ground level. It is coupled to the low speed shaft through an elastromeric teeter bearing. A 2500 kW synchronous generator is driven via a step-up planetary gear box and "soft" quill shaft. The generator, gearbox, hydraulic systems, electronic controls and other support equipment are enclosed in a nacelle mounted atop a cylindrical steel tower. The nacelle can be yawed (rotated) to keep the rotor oriented correctly into the wind as the wind direction changes. A hydraulic pitch control system is used to control the position of the movable rotor tips. The movable rotor tips are used to obtain the rated rotational speed of 17.5 rpm, and to maintain the proper power output at wind speeds above rated wind speed (27.5 mph @ hub).

The WTS is controlled by an electronic microprocessor. The microprocessor is designed to allow unattended operation of the WTS at a remote site. The microprocessor monitors wind conditions and the operational status of the wind turbine. Equipment failures result in automatic shutdown of the WTS. The systems status is monitored at the utility substation, from which maintenance crews are dispatched as needed.



Rated power	2,500 KW
Rotor diameter	300 ft
Rotor type	Teetered - tip control
Rotor orientation	Upwind
Rotor airfoil	NACA 230XX
Rated wind @ hub	27.5 mph
Cut-off wind speed @ hub	45 mph
Rotor tip speed	275 ft/sec
Rotor rpm	17.5
Generator rpm	1,800
Generator type	Synchronous
Gear box	Compact planetary gear
Hub height	200 ft
Tower	Soft-shell type
Pitch control	Hydraulic
Yaw control	Hydraulic
Electronic control	Microprocessor
System power coefficient	0.382

Figure 3-1. MOD-2-107 Configuration Features & Characteristics

3.2 ROTOR

The MOD-2 WTS has a steel, two bladed, teetering, tip control type rotor with continuous carry-through structure at the hub. It utilizes a NACA 230XX series airfoil rotating at 17.5 rpm (275 ft/sec tip speed). The basic construction is a welded steel shell with steel spar members.

As shown in Figure 3-2, the rotor is divided into three primary sections: the tip, the mid-section, and the hub section. The tip (outer 30%) is rotated with respect to the remainder of the blade to control rotor speed and power. The tip and mid-sections are the working portions of the blade. The hub section is attached to the mid-section with a field splice and is a transition from an airfoil cross-section to an oval cross-section.

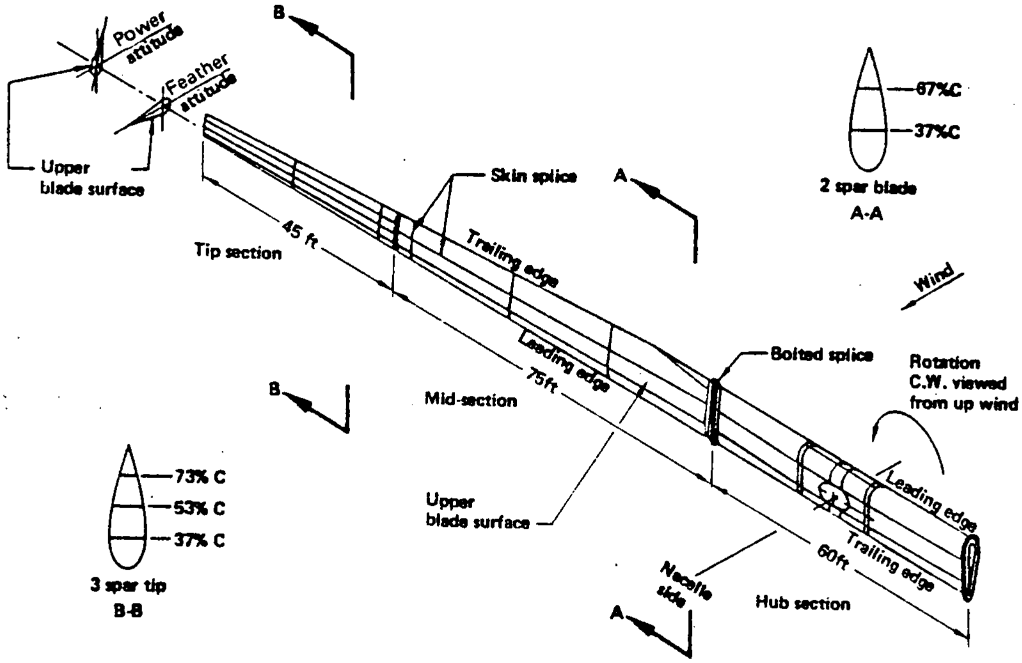


Figure 3-2. Rotor Blade Configuration

Each tip is controlled by means of a hydraulic actuator mounted on the blade mid section adjacent to the tip section as shown in Figure 3-3. The flow control to the actuators is governed by a signal from the automatic control system to servo valves. The position of the tips is monitored by position transducers and fed back to the control system. The normal rate of rotation of blade tips is from 0.1 to 1 degree per second.

In the event of a major system failure, the actuators drive the blade tips to the feathered position at rates of 4 to 8 degrees per second (depending on actuator position), using energy stored in separate hydraulic accumulators. The pitch rates are such that under any failure mode no overspeed will exceed 15% of normal rpm. Redundancy is provided by the ability of either one of the operating actuators to shut down the system should one actuator become inoperative. Locks are provided to hold the blade tips in the feathered position when the hydraulic system is depressurized.

The blade tip section with the spindle assembly and the hydraulic actuator are attached to the blade mid section as a unit (Figure 3-3). The attachment is made by 6 bolts for ease of assembly and removal. Either blade tip can be removed independently from the WTS. The spindle protrudes into the blade mid section in a way to provide a load path for centrifugal and bending moments. Tapered rings at the outboard rib and a close tolerence bushing at the inboard rib assure a tight fit between the spindle sleeve and the mid-section of the rotor. The bearings are lubricated by a long-life grease.

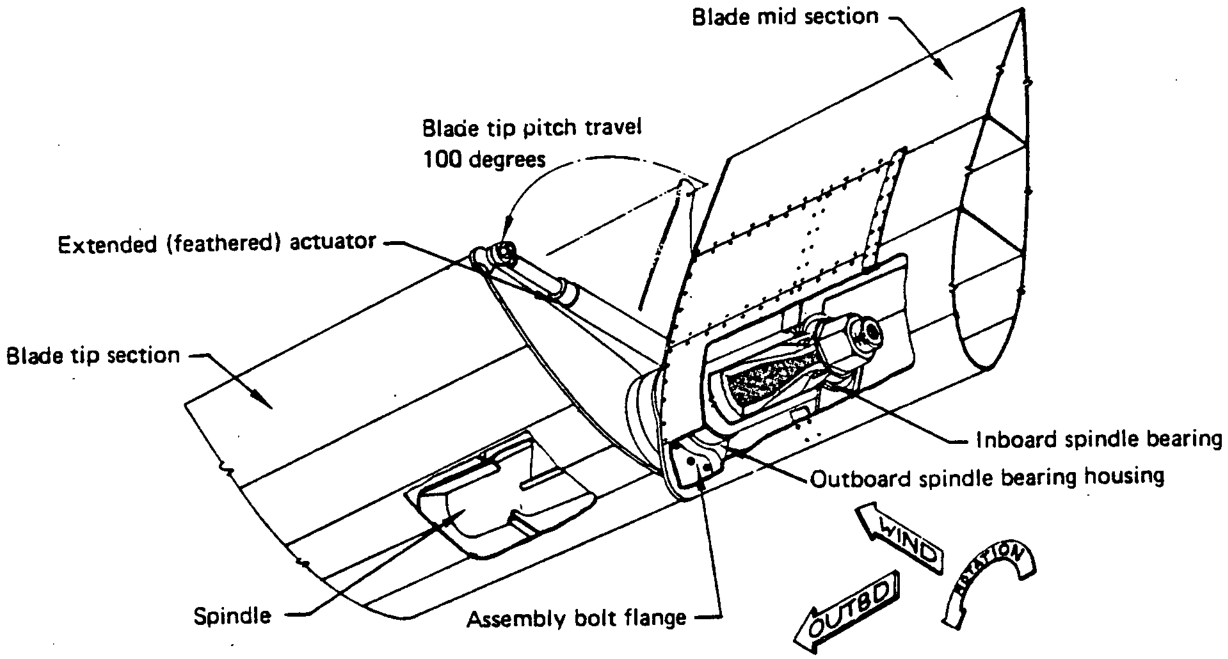


Figure 3-3. Tip Spindle Installation

The pitch control hydraulic system consists of an electrical motor driven pump, reservoir, accumulators, filters, heat exchanger, control valves, associated plumbing and actuators. Hydraulic components not located in the blade are installed on, and rotate with, the low speed shaft (Figure 3-4). Electrical power and control signals are transferred from the nacelle electric power and control unit by brushes and a slip ring assembly.

Because the hydraulic system is located in a rotating environment, special attention has been extended to design for this environment. The components on the low speed shaft are exposed to approximately 1.3 g's and the reservoir has been tested in this environment with no adverse effects. The blade tip control actuator, rotating in an 11 g environment, has been selected with oversize rod and piston bearings, and is in the retracted position when exposed to this environment.

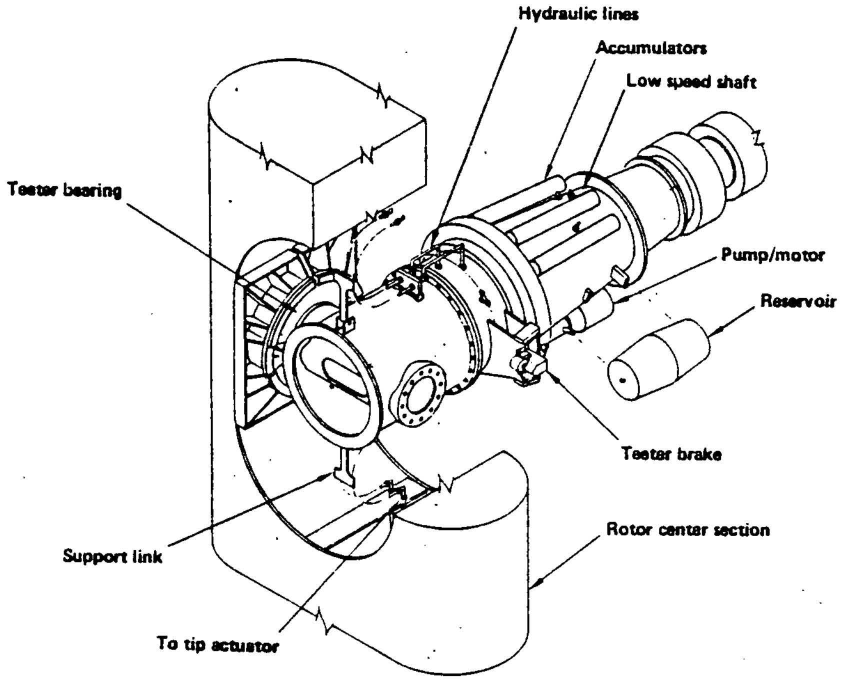


Figure 3-4. Pitch Control Hydraulics

The attachment of the rotor to the low speed shaft is by a teeter type bearing, which minimizes the one-per-revolution blade flapwise loads and the effects of small unsymmetric gusts, resulting in reduced fatigue loads. The teeter motion takes place in two elastomeric radial bearings which also transmit the rotor output torque into the rotor low speed shaft (Figure 3-5). The use of the elastomeric bearings eliminates lubrication requirements and prevents fretting that would be likely to occur if roller bearings were used. The elastomeric bearings consist of concentric alternate layers of sheet steel and rubber bonded together forming a package that is highly flexible in torsion and has sufficient radial load capability. Trade studies showed that use of the teeter hub in place of rigidly mounted blades not only reduces the weight of the rotor assembly but also the tower and nacelle weights, thus reducing fabrication and material costs.

Stops are provided to limit teeter motion to $\pm$ 5 degrees. A teeter brake is provided to prevent rocking when the rotor is in the standby mode, and to dampen teeter excursions during starting and stopping. During erection, the rotor, with teeter bearings and upwind end of the low speed shaft installed, can be lifted in one piece and bolted in place at the low speed shaft bolt flange.

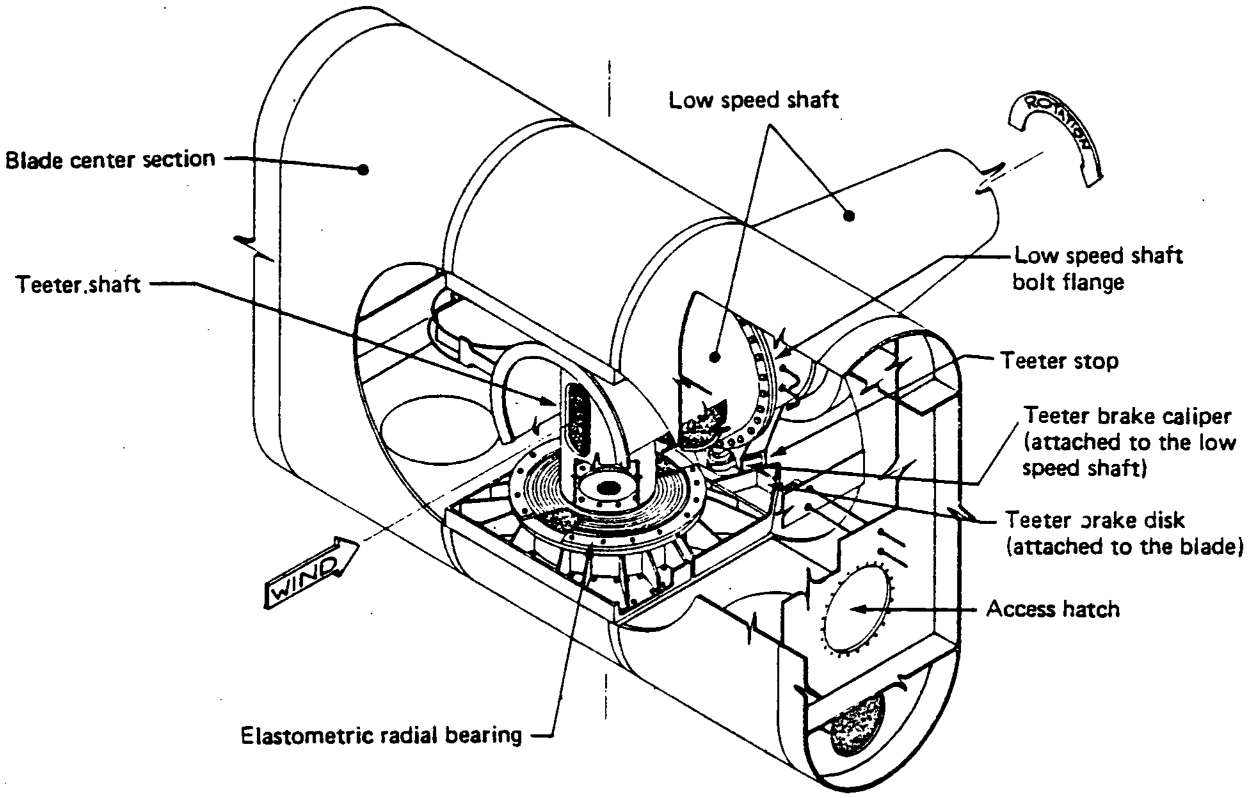


Figure 3-5. Teeter Bearing Installation

The entire rotor assembly is sealed, to allow use of a flow type crack detection system. The occurence of a significant crack in the rotor structure will result in WTS fail-safe shutdown.

3.3 DRIVE TRAIN

The drive train subassembly consists of a low speed shaft, quill shaft, gearbox, high speed shaft, couplings, rotor parking brake, and generator. These major components are shown in Figure 3-6.

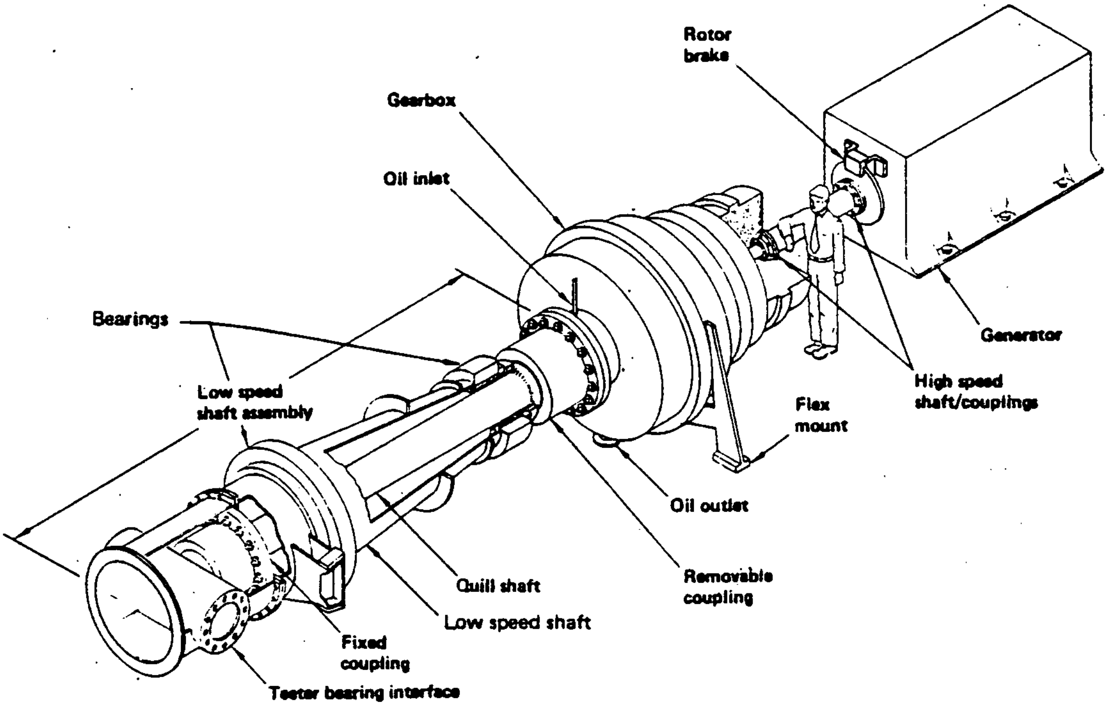


Figure 3-6. Drive Train

The large diameter low speed shaft transfers the rotor forces into the nacelle structure through the two shaft support bearings. The forward bearing supports the radial load while the aft bearing transfers both thrust and radial loads to the nacelle. The rotor torque is transmitted to the gearbox through the "soft" quill shaft. The purpose of the softness is to reduce the two-per-revolution rotor torque fatigue effects at the gearbox and to improve the quality of the generator output.

A 103:1 step-up of rpm from 17.5 to 1800 rpm is provided by a three stage epicyclic gearbox, which is smaller, lighter in weight, less expensive, more efficient and more tolerant to support deflections than a parallel shaft type gearbox with a similar rating. The low weight of the gearbox (39,000 lbs) enhances the overall design of the supporting structure. It is flexibly mounted to the nacelle to reduce the effect of nacelle deflections on gear loads. Maintenance is enhanced by the small size of the gearbox. Major repairs can be accomplished in the nacelle.

The generator is a synchronous electrical generator, rated at 2500 kW. The unit is an open frame, drip proof, four salient pole brushless machine that operates at 1800 rpm and has a shaft mounted exciter.

The rotor parking brake prevents rotor rotation when the WTS is not running. This prevents gearbox damage due to rotation without lubrication. The braking mechanism consists of a disc mounted on the high speed shaft and a spring actuated brake attached to the generator frame. The brake is disengaged by an electrically actuated hydraulic valve and engaged by spring force when the electrical circuit is open. The disc utilizes a replaceable element to minimize maintenance time in the event of brake disc wear.

As a result of the FMEA and maintainability studies, a positive mechanical lock mechanism is incorporated in the low speed shaft. This prevents rotation of wind turbine during maintenance periods.

3.4 NACELLE

The nacelle houses the major subsystems of the MOD-2 WTS such as the drive train, generator with its accessories, yaw bearing and drive, and associated hydraulic systems for pitch and yaw control as is shown in Figure 3-7. Other equipment in the nacelle includes generator cooling air ducts, gearbox oil cooling radiators, maintenance lighting fixtures and wall plugs, electronics cooling and heating system, general nacelle air circulating system, fire protection, and maintenance support equipment.

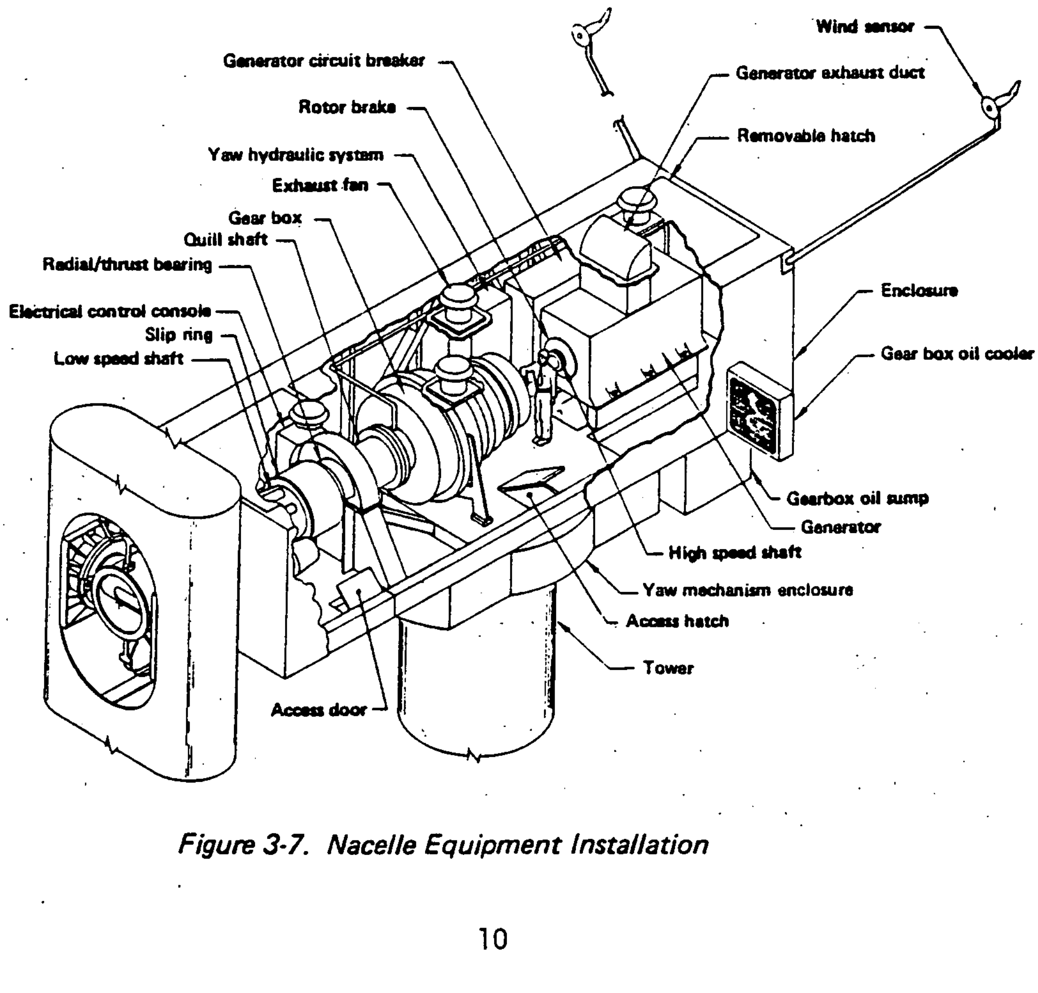


Figure 3-7. Nacelle Equipment Installation

The primary functions of the nacelle are to provide a rigid mounting platform for the system components, react to rotor loads and provide environmental protection for the components.

The nacelle structure is of welded steel truss construction. Its primary dimensions are: 36.8 feet long, 9.3 feet high, and 11.3 feet wide. The top and sides are sheathed with corrugated steel sheets, and the floor is steel safety plate. A central floor hatch provides normal access from the tower, while hatches at either end provide emergency egress by means of a non-powered emergency man-lowering device.

Other primary considerations in the design of the nacelle were maintainability and safety. The MOD-2 design utilizes two overhead monorails for equipment handling. One of these extends through a large door in the downwind side of the nacelle. It can be used in conjunction with a portable hoist to raise equipment from the ground. There are also large overhead hatches for the installation or removal of large pieces of equipment. Care has been taken to allow sufficient room for maintenance procedures to occur within the nacelle.

Safety features of the nacelle are the integral fire extinguisher system, the emergency hatches and lowering devices, the ability to remove an injured person on a stretcher, and the positive mechanical shaft locking device.

The nacelle also houses the yaw drive system. The yaw system connects the nacelle to the tower as is shown in Figure 3-8. It rotates the rotor into the wind at a rate of 1/4 degree per second, and holds it in position as commanded by the yaw control system. All rotor and nacelle loads are transferred to the tower through the yaw bearing which is of a crossed roller configuration with an internal ring gear. The raceway diameter is approximately 120 inches in order to handle the large overturning moments and to react to the rotor torque.

Proper nacelle orientation to the wind is maintained by the yaw control system. The control system utilizes a wind sensor to determine wind direction and maintain nacelle position to within ± 7 degrees of wind direction so as to minimize power losses. To allow for the short-period wide-directional variations common at low wind speeds, the yaw control system uses a thirty second average to determine wind direction. If the average over a 5 minute period exceeds ± 7 degrees, the control system initiates a corrective yaw drive. If a $\pm 20^{\circ}$ tolerance is exceeded for more than 2 minutes, the control system initiates shutdown.

The yaw drive system operates at 2000 psi and consists of an electric motor, hydraulic pump, heat exchanger, reservoir, accumulator, filters, and the necessary valves and tubing. The hydraulic motor runs a pinion meshing with the gear on the inner race of the yaw bearing.

A hydraulic brake is applied to provide damping during yaw motion. An additional six brakes hold the nacelle from inadvertent yawing due to wind loads during "no yaw" operation. The yaw brake calipers are spring actuated and hydraulically released through the yaw drive hydraulic system. This is a failsafe feature assuring that the brakes are applied if there is a hydraulic failure. The brake disc has a replaceable element to minimize maintenance time if there should be excessive wear. A weather shield surrounding the yaw drive system provides both weather protection and a platform from which yaw brake and bearing maintenance can be performed.

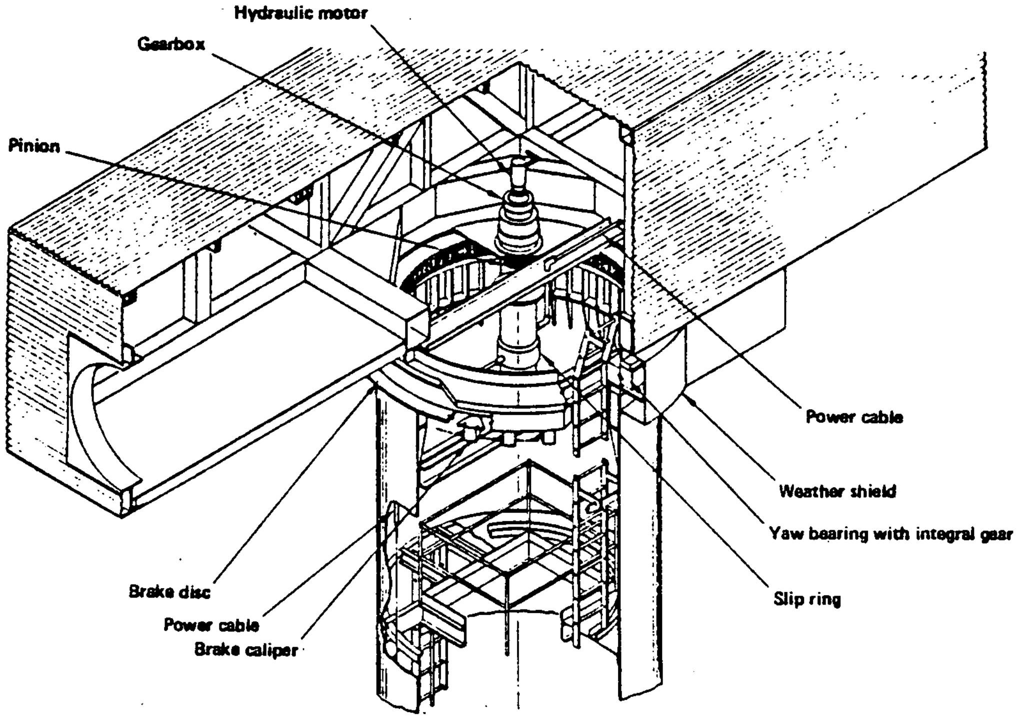


Figure 3-8. Yaw Drive Installation

3.5 TOWER/FOUNDATION AND FACILITY LAYOUT

The nacelle assembly is supported by a 193 foot tall cylindrical welded steel tower. The tower is 10 feet in diameter with a base section flaring to 21 feet in diameter at the ground. It is bolted to a foundation of reinforced concrete. In normal soil conditions, a buried octagonal stepped foundation configuration will be used as shown in Figure 3-9.

The tower is designed to have a low natural bending frequency (approximately 1.3 per rotor revolution) to reduce the alternating rotor loads transmitted to the tower.

The tower contains an internal lift to provide transportation from the ground to nacelle. The lift ends at a platform near the top of the tower, with final nacelle access by a ladder as shown in Figure 3-8. A ladder with safety rail runs the entire height of the tower to allow access in the event of a lift failure. The power cable runs from the electrical slip ring at the top of the tower, down the tower side, thence to the bus tie contactor unit located on a separate concrete pad external to the tower (Figure 3-10.) A step-up transformer is also located on this pad. Additional electrical and control equipment (primarily the uninterruptible power supply) is located in the tower base. The power cable lines are buried from the tower to the utility connection at the transformer pad.

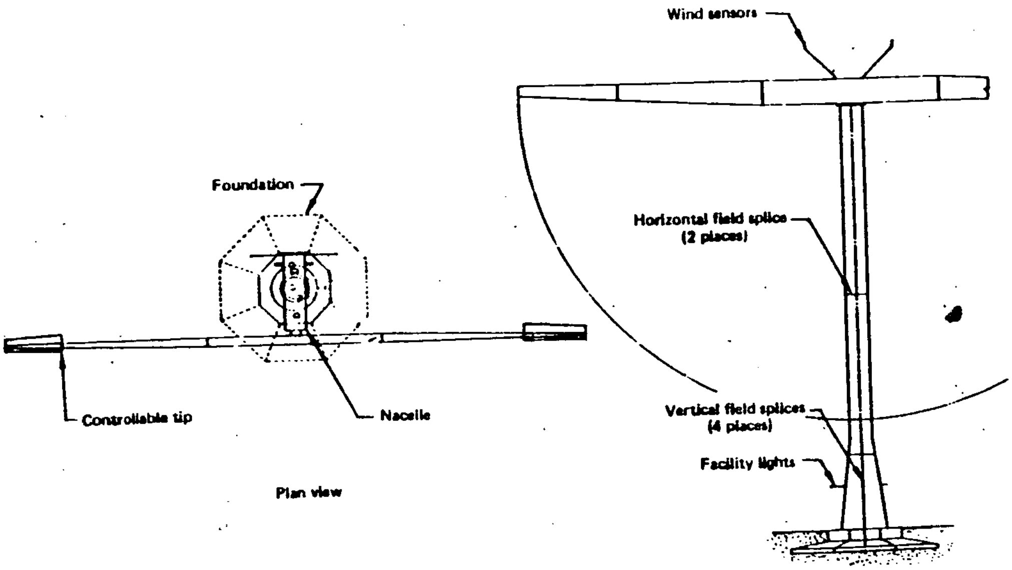


Figure 3-9. Tower/Foundation

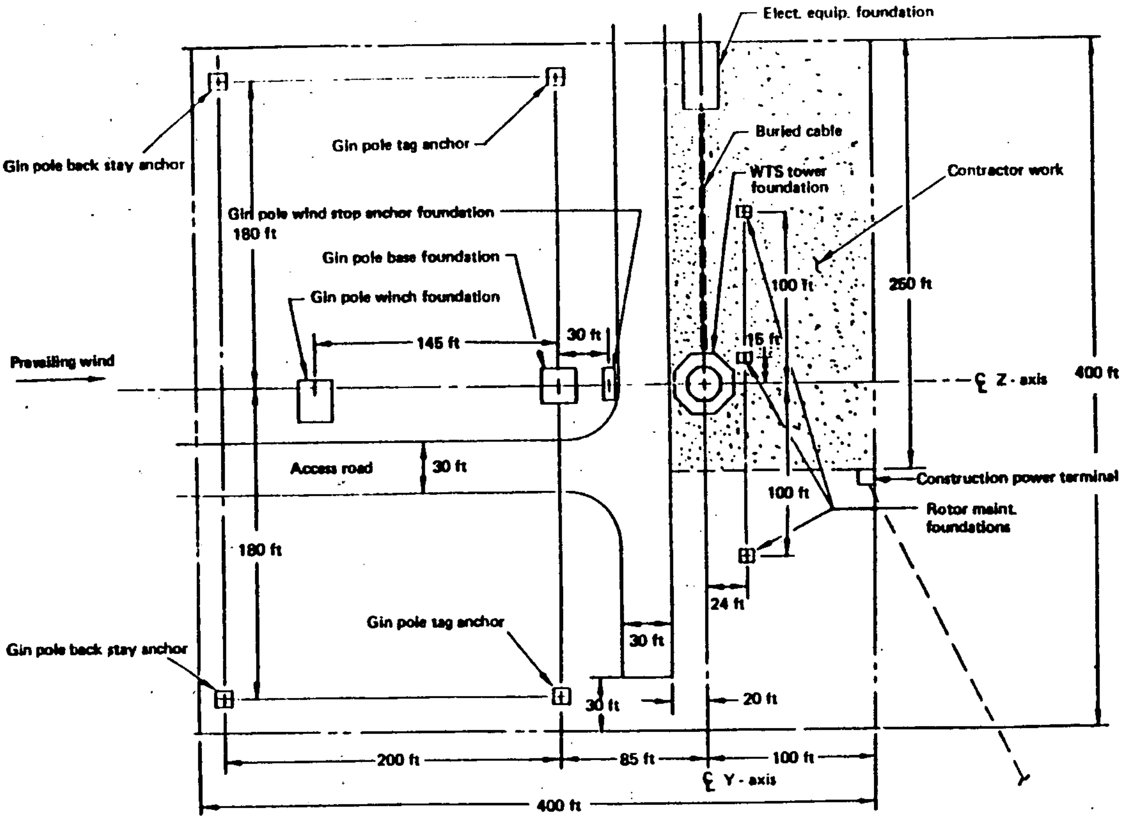


Figure 3-10. Facility Layout

3.6 ELECTRONIC CONTROL SYSTEM

The control system provides the sensing, computation, and commands necessary for unattended operation of the WTS as shown in Figure 3-11.

The controller is a microprocessor which is located in the nacelle control unit and initiates start-up of the WTS when the wind speed is within prescribed limits. After start-up, it computes blade pitch and nacelle yaw commands to maximize the power output for varying wind conditions. Continuous monitoring of wind conditions, rpm, power and equipment status is also provided by the microprocessor which will shut down the WTS for out-of-tolerance conditions.

A control panel and CRT terminal are located in the tower base to provide operating and fault data displays and manual control for maintenance. A remote CRT terminal at the utility substation will provide display and limited WTS controls.

The WTS is protected from computer system failure by an independent failsafe emergency shutdown system. This system provides sensor redundancy on critical components, and initiates shutdown independent of the primary control system when necessary. The design of the failsafe system was governed by the results of the FMEA.

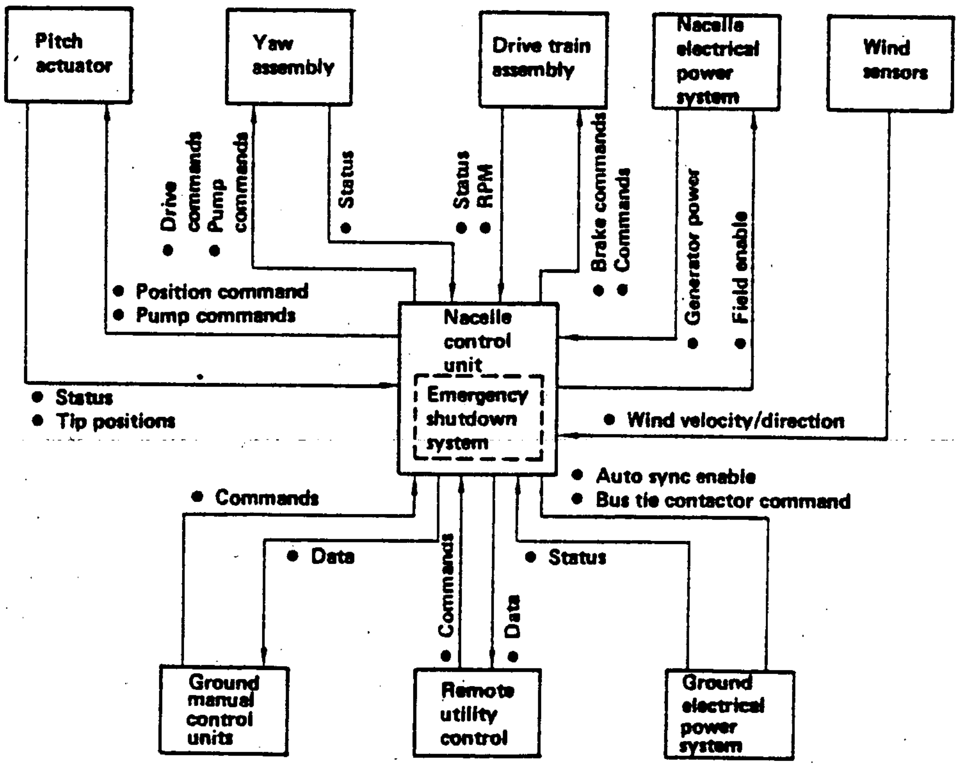


Figure 3-11. Control System Block Diagram

The software for the controller occupies approximately 12 thousand bytes of programmable read-only memory with an additional four thousand bytes of random access memory for operating and history data storage. The software control cycle is accomplished at a rate of 10 Hertz to provide a one Hertz response digital feedback control to the blade pitch system. In addition, each program cycle also samples all sensors, schedules the proper operating mode, and generates commands as required to control nacelle position with respect to the wind.

3.7 ELECTRICAL POWER SYSTEM

The WTS electrical power system is designed to deliver power to a utility transmission network. The system consists of the electrical equipment required for the generation, conditioning and distribution of electrical power to the utility and within the WTS as shown in Figure 3-12. In normal operation, the generator receives its power in the form of torque at synchronous speed from the gearbox. Electrical power at appropriate voltage is delivered at a utility interface point which is the output side of a fused manual disconnect switch located at the transformer pad. Once the WTS and the utility are electrically connected, the existence of the tie will automatically result in generator voltage and frequency control since the utility power grid is effectively an infinite bus to the WTS. Thus constant generator and rotor rpm will be maintained.

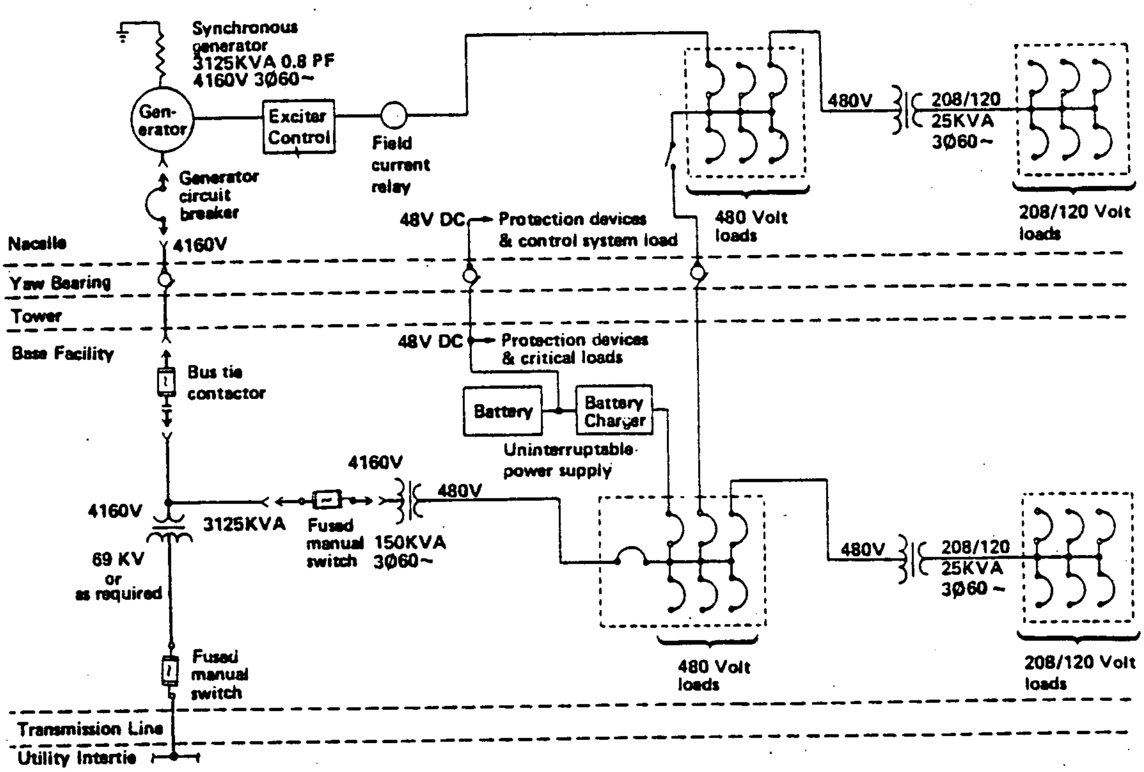


Figure 3-12. Electrical Power System Block Diagram

The MOD-2 electrical power system employs a four pole synchronous generator containing an integral brushless exciter. It is a 3 phase, 60 Hertz, 4160 volt generator rated to provide 3125 KVA at 0.8 power factor; i.e., 2500 kW, at altitudes to 7,000 feet, or temperatures to 50 degrees C. This generator choice is based upon the results of the trade studies, and the requirement for operation at altitudes to 7,000 feet above sea level. Excitation control is provided to maintain proper voltage prior to synchronization with the utility and to provide a constant power factor output afterwards.

Protective relays are provided to guard against potential electrical faults, out-of-tolerance performance, or equipment failures. These relays will detect over-voltage, loss of excitation, underfrequency, overcurrent, reverse phase sequence, reverse power and differential current, and will protect the system by inhibiting synchronization, directing the control system to shut down or, if required, trip the generator circuit breaker. The operation of these protective relays was governed in part by the results of the FMEA.

Power is delivered to the utility transmission line through a bus tie contactor. Its operation is controlled by automatic synchronization equipment, located at the tower base. Accessory power for operation, control and maintenance is obtained from the utility or generator output depending on the operating mode, and is internally conditioned to appropriate voltage levels. A battery, floating across a charger, provides an uninterruptable power supply for operation of protective devices and critical loads.

3.8 SYSTEM PERFORMANCE

The performance of the MOD-2 WTS is specified by its system efficiency curve, its power and energy output distributions, and its annual energy output.

The efficiency of the MOD-2 WTS is described by a nondimensional number known as the power coefficient. Physically, the power coefficient is that fraction of the wind's kinetic energy passing through the rotor disk which is converted into electrical energy.

The system power coefficient for the MOD-2 WTS is shown in Figure 3-13. As indicated on the figure, the system power coefficient is derived from the rotor power coefficient and the efficiencies of the drive train and electrical subsystems. Also indicated on Figure 3-13 is a rated power line for 2500 kW at sea level standard conditions.

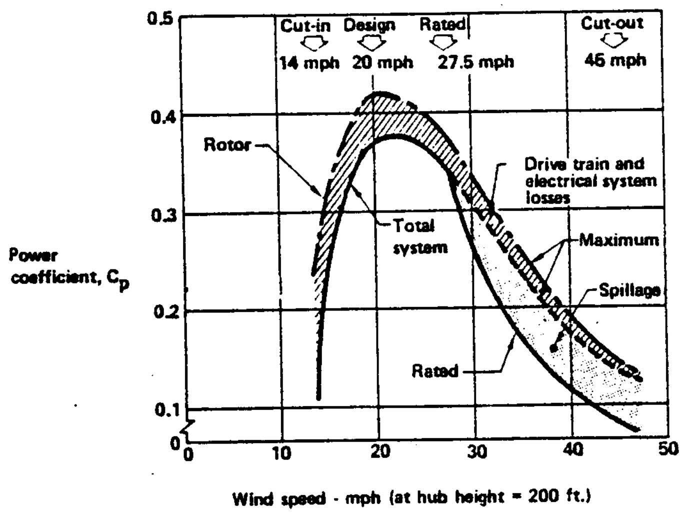


Figure 3-13. Cp Versus Wind Speed — Sea Level STD

The system efficiency curve can be translated into a power distribution curve for any given atmosphere density. The MOD-2 system power output distribution is shown in Figure 3-14 for standard temperature at sea level and 7,000 foot altitude. The cut-in, rated and cut-out wind speeds are also indicated on this figure. The rated wind speed is predicated upon use of a 2500 kW generator. The cut-in and cut-out wind speeds were selected in a trade study which is discussed in the Volume II, Detailed Report. The indicated cut-in wind speeds correspond to a power output of approximately 125 kW.

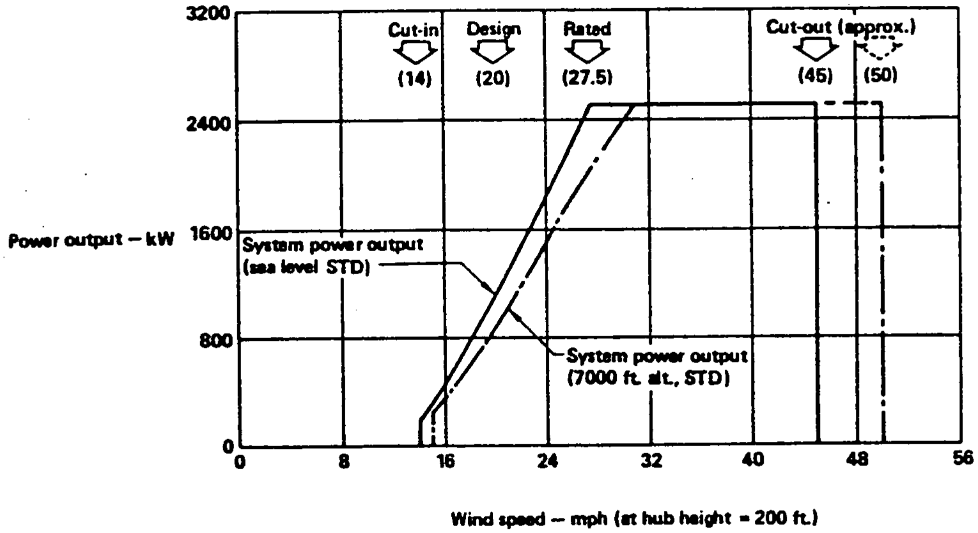


Figure 3-14. System Power Output Versus Wind Speed

The energy output frequency distribution for the MOD-2 WTS is derived by combining the power distribution curve with the wind frequency distribution for a given site. The energy output frequency distribution for the MOD-2 WTS is shown in Figure 3-15 for sea level standard conditions. The associated wind frequency distribution is presented in Figure 3-16. This wind frequency distribution is at a site with a mean wind speed of 14 mph at a height of 30 feet. The 14 mph mean wind speed frequency distribution represents sites where the MOD-2 is expected to be placed and was used for optimization of the WTS characteristics.

The area under the curve is indicative of the time the WTS spends in different operating regimes. Approximately 59% of the time the WTS experiences winds between cut-in (14 mph) and rated (27.5 mph), while 18% of the time the wind speed is between rated and cut-out (45 mph). The remaining time (23%) the wind turbine experiences either winds too light or too strong for operation. Of this idle time, most occurs due to low wind speeds.

The annual energy output of the MOD-2 WTS is obtained by integrating the energy frequency distribution between the cut-in and cut-out wind speeds. For the MOD-2 WTS the total annual energy is 9,750,000 kWh, including the 0.967 system availability. The MOD-2 WTS derives 61% of its energy when operating between the cut-in and rated wind speeds, while 39% of the annual energy is derived when operating above rated wind speed.

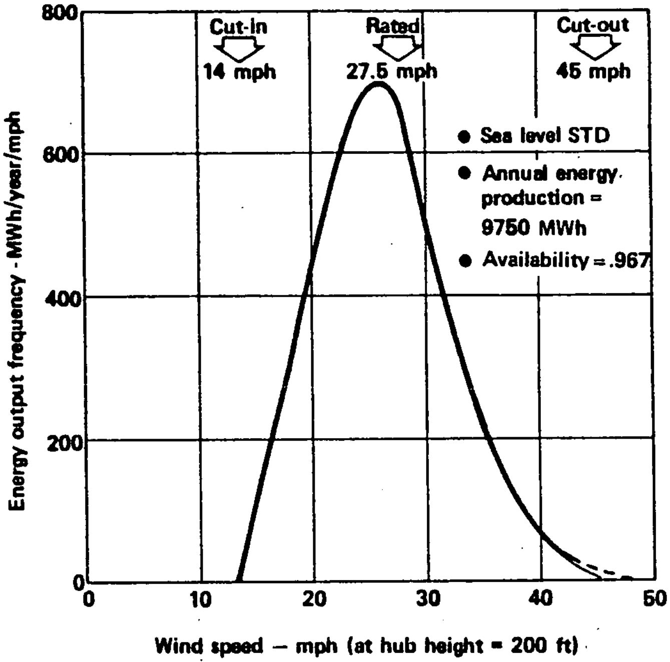


Figure 3-15. Energy Output Frequency Distribution

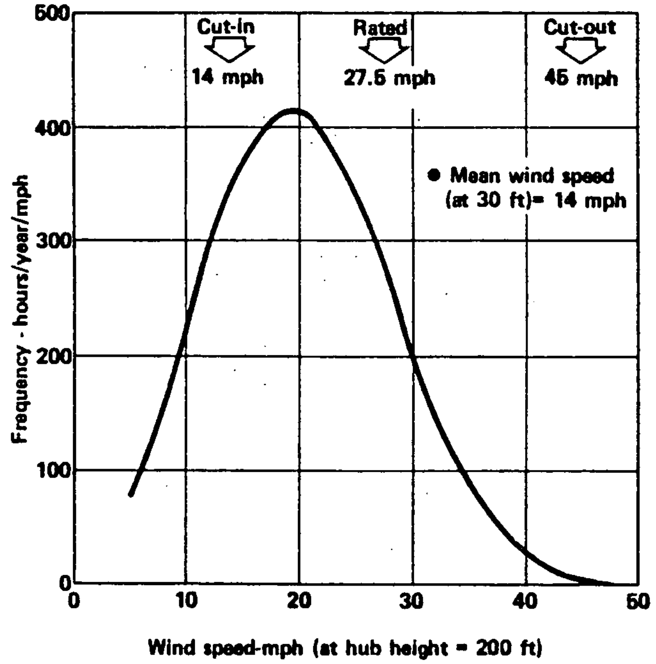


Figure 3-16. Wind Speed Frequency Distribution

3.9 SYSTEM WEIGHT

The MOD-2 system weight breakdown is shown in Table 3-1. The weights are estimates based either on calculation of preliminary design drawings, supplier weight estimates or vendor catalog date. The design represents a low unit weight of 232 lb per kW (0.06 lb/kWh). This light weight contributes significantly to the low cost of energy.

Table 3-1. Tier III Weight Report

Group	Element	Weight (lbs)
41	Blade	100,336
42	Hub	67,722
43	Pitch control	1,509
41-43	Rotor subassembly	169,567
51	Lo speed shaft + bearings	22,865
52	Quill shaft + coupling	9,483
53	Gearbox	39,000
54	Hi speed shaft + coupling	600
55	Rotor brake system	280
56	Lubrication system	6,664
57	Generator	17,000
51-57	Drive train	95,892
61	Nacelle structure	33,680
63	Yaw drive	17,742
64	Rotor support structure	7,152
65	Environmental Control + fire	870
66	Cabling + electrical facilities	645
67	Instruments + controls	690
68	Gen. accy. unit	2,500
61-68	Nacelle	63,279
71	Tower	246,536
72	Cable installation	4,130
73	Cable transition	500
74	Lightning protection	300
71-74	Tower subassembly	251,466
41-74	Total above foundation	580,204

3.10 COST OF ELECTRICITY

The primary objective in the development of the MOD-2 is to produce energy at a cost of electricity under 4 ¢/kWh based on 1977 cost forecasts. The projected cost of electricity for MOD-2 is 3.3 ¢/kWh. The cost is for the 100th WTS unit produced in a commercial production rate facility and installed in a cluster of 25 units.

Estimated 100th production unit costs for the MOD-2 WTS are summarized in Figure 3-17. The turnkey estimates include all costs associated with the manufacture, assembly and installation of the WTS. The detailed derivation of these costs is provided in Volume II, Detailed Report.

Turnkey account		Cost
1.0	Site preparation	$162,000
2.0	Transportation	29,000
3.0	Erection	137,000
4.0	Rotor	329,000
5.0	Drive train	379,000
6.0	Nacelle	184,000
7.0	Tower	271,000
8.0	Initial spares	35,000
8.A.	Non-recurring	35,000
9.0	Total initial cost	$1,561,000
	Fee (10%)	156,000
	Total turnkey	$1,717,000
10.0	Annual operations and maintenance	$15,000

The cost estimating ground rules are as follows:

- All costs are in mid 1977 dollars
- Costs are fully burdened and a 10% fee is included
- Costs of installation and operation are based on a 25 unit farm
- Rate of installation is one WTS per month per farm
- Sites are generally flat with few natural obstacles and soil is easily prepared for foundation (land cost not included)
- Transportation costs are based on rail and truck transport over a distance of 1,000 miles

Figure 3-17. 100th Production Unit Costs

The 25 unit farm has a total rated power of 62.5 MW. Each unit contains a step-up transformer that increases the generator output voltage to 69 kV for transmission. Costs beyond the step-up transformer are not included in the turnkey costs.

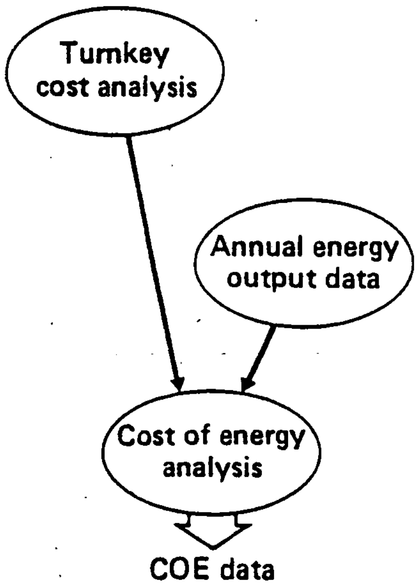
The cost of electricity is derived from the turnkey costs coupled with annual O&M costs, annual energy output and availability. The energy pricing method used to project the MOD-2 WTS energy costs is the levelized fixed charge rate approach. It derives a levelized energy price necessary to recover the costs to a utility for purchasing, installing, owning, operating, and maintaining a MOD-2 WTS. The specific formulation used for the cost of electricity calculation is shown in Figure 3-18. A summary description of each term in the equation follows:

FCR = levelized fixed charge rate which includes return on capital, income tax, property tax, and insurance. FCR is sensitive to cost of capital, capitalization method, income tax rate, and system lifetime.

IC = initial turnkey cost of the energy system which includes complete cost exposure to the utility for purchasing, installing and setting up logistics for the energy production system.

AOM = Annual operation and maintenance (O&M) cost which includes operating budgets and maintenance budgets.

AEP = anticipated annual energy production of the energy system. AEP takes into account energy production losses attributed to the unavailability of the energy system equipment and the unavailability of the energy source (i.e. wind).



- **Cost of electricity**

$$COE = \frac{IC \times FCR + AOM}{AEP}$$

- **FCR = annualized fixed charge rate = 18% per year**
- **IC = total WTS cost=$1,720,000**
- **AOM = annual operations & maintenance cost = $15,000**
- **AEP = annual energy production = 9.75 x 10^6 kWh**
- **COE = 3.3 ¢/kWh**

Figure 3-18. COE Determination

4.0 SYSTEM DEVELOPMENT

As discussed in Section 2.0 and Figure 2.1, the cost effective MOD-2 WTS was developed from an extensive evaluation of design trade-offs. These studies evaluated the sensitivity to system specifications, the optimum machine sizing for the wind spectrums, optimization of basic design concepts, system and component variations, and the manufacturing, assembly, installation, and test scenarios for minimum cost of electricity.

4.1 TRADE STUDY SUMMARY

This section lists the trade studies performed (see Table 4.1) which developed the recommended MOD-2 WTS configuration and summarizes the results of the more significant trade-offs. For a detailed discussion of the data, rationale and results of these studies, the reader is referred to Volume II, Detailed Report of this documentation.

Figures 4-1 and 4-2 depict two most significant trade studies which illustrate the optimization of the size of the MOD-2 for the specified wind environment defined by the mean wind speed of 14 mph. The rotor diameter of 300 feet for a generator rating of 2500 kW is optimum and provides the near optimum design over a significant range of wind environments.

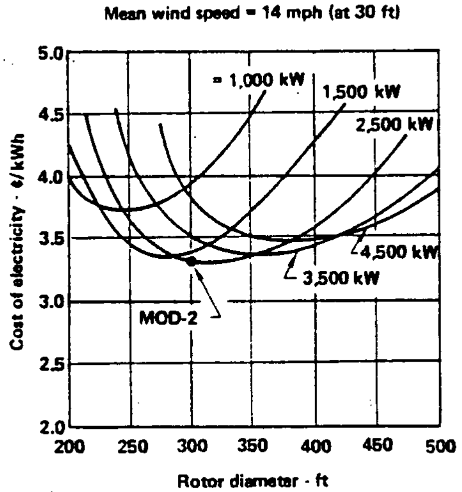


Figure 4-1. Parametric COE Trends

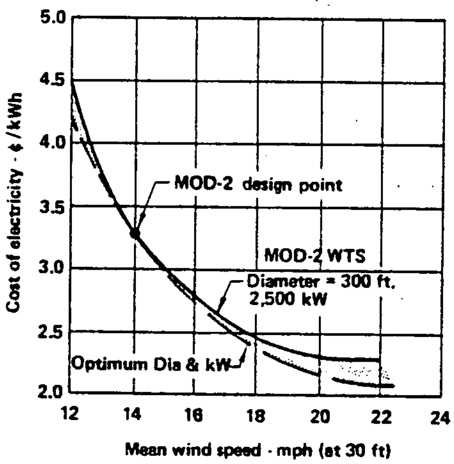


Figure 4-2. Effect of Mean Wind Speed on COE

TABLE 4.1 SUMMARY OF TRADE STUDIES

TRADE	SELECTED CONFIGURATION	REMARKS
Fixed vs. variable speed rotor	Fixed speed rotor	Variable speed captures more energy but adds 0.57¢/kWh
Cut-in wind speed - low	14 MPH @ hub height	11 mph req'd to sustain rated rpm. 3 mph margin avoids frequent stop/start cycles
Cut-out wind speed - high	45 mph @ hub height	Total energy available above 45 mph is less than 1% for specified wind spectrum
Design Wind Speed	20 mph @ hub height	Maximum specific energy output for design specific power power rating of 35.4 watts/sq. ft.
Rated Wind Speed	27.5 mph @ hub height	Compatible with design wind speed
Design Power Rating	2500 KW generator	Minimum COE for specific power of 35.4 watts/sq. ft. in specified 14 mph wind spectra
Design Service Life	30 years	Minimim COE considering periodic component replacements
Extreme Wind Speed	120 mph @ 30 ft.	Optimum for sites with highest occurrence of high winds such as Florida and Cape Hatteras. Negligible penalty at typical sites
Machine Size Optimization	2500 KW Generator 300 ft. dia. rotor	Minimum COE for Site with 14 mph mean wind. See Figure 4.1
Mean Wind Speed	Specification value = 14 mph	MOD-2 near optimum over typical site mean winds. See Figure 4.2
Two vs. Three Blade Rotor	Two blade rotor	Increased energy output of 3 blades more than offset by increased system costs.
Teetered vs. Rigid Rotor	Teetered rotor	Total WTS weight reduces 61,000 lb. COE reduced 0.14¢/kWh
Teeter Stop Study (Brake vs. rigid vs. spring vs. viscous damper)	Friction brake & rigid stop	Brake concept reduces risk and controls teetering when parked
Teeter Bearing Study (Roller vs. plain vs. elastomeric)	Elastomeric Bearing	Least complex, no lube system and seals required
Optimum Rotor Speed	17.5 rpm	Maximum energy output at 17.5 rpm Higher rpm reduces system weight and cost, but not sufficiently to overcome energy loss
Partial vs. Full Span Rotor Control	Partial (30% Tip)	Reduces loads, less complex hub, reduced weight, and COE reduces = 0.4¢/kWh
Aluminum vs. Steel Tip Blade	Steel Tip Blade	Steel is negligibly heavier due to fatigue critical loads. Steel tip approx. $16,000 cheaper. Eliminates development work on aluminum structure
Airfoil Geometry (NASA 230XX vs. 430XX vs. 44XX and modifications)	NASA 230XX	For equal performance, the selected airfoil results in lightest rotor and least COE

TRADE	SELECTED CONFIGURATION	REMARKS
Blade T.E. Configuration (welded steel plate vs. foam-filled fiberglass vs. steel skinned honeycomb panels & others)	Welded Steel Plate	Minimum cost and risk
Crack Detection System	Low Pressure flow through orifices	Cost effective means to provide early crack detection and WTS shutdown prior to failure
Crack Stopping Design	Not Practical	High risk structure
Metal vs. Composite Rotor	Metal rotor	Composite requires further development and is higher risk. Complicated pivet joint and hub to mid blade joint
Upwind vs. Downwind Rotor	Upwind Rotor	Higher energy output reduces COE
Tip to Ground Clearance	50 feet	Larger values of ground clearance increased power output, but offset by increased system costs
Tilted vs Non-Tilted Rotor	No tilt	Small tilt angles can be accommodated if required for blade/tower clearance. Tilt above 4-5 degrees increases COE.
Epicyclic vs. Parallel Shaft Gear Box	Epicyclic Gearbox	Lower weight, lower cost, higher efficiency. COE reduced 0.55¢/kWh
Low Speed Shaft Support Configuration (Fixed vs. Inplane vs. Rotating)	Rotating Shaft support	Lowest risk, lightest weight, least COE
Generator Drive Selection (Direct vs. Gearbox Driven)	Gearbox Driven	Direct driven generator at 2500 kw would require 50 feet diameter pancake shape with $\leq$ 400 poles High weight & high cost
Power Generation (60 Hertz Direct vs. Static Inverter)	60 Hertz Direct (constant speed)	Static Inverter systems adds considerable cost. COE would increase 0.57¢/kWh
Generator Type Selection (Synchronous vs. Induction)	Synchronous Generator with soft quill shaft	Less risk, control understood COE reduced 0.035¢/kWh
Generator Speed Selection (1200 vs. 1800 rpm)	1800 rpm	Less generator cost, less drive train torque, gearbox not significantly costlier. Net COE reduction
Generator Voltage Selection (4.16 KV vs. 13.8 KV)	4.16 KV with transformer	Provides flexibility for multi-unit farm installations. 4.16 is standard for 2.5 mw generator. Smaller and lighter. Least system cost
Generator Selection (Effect of site altitude)	One design - standard commercial generator	Slightly derated at 7000 ft - hot day. Could accommodate extreme environment range with modified design at slight cost

TRADE	SELECTED CONFIGURATION	REMARKS
Desirability of Emergency Deisel Driven Generator	No emergency generator	48 vdc - 50 amp-hour batteries handle requirements in the event of utility power loss
Generator Circuit Breaker (Nacelle vs. Ground Level)	Nacelle Located GCB	Eliminates additional yaw slip rings. Less complex, more reliable and least cost
Wiring Transfer Across Yaw Bearing (Slip ring vs flex cables)	Slip Ring	Nacelle rotation not limited. Flex cable would require development and test with high risk of limited life
Nacelle Yaw Drive (Electric vs. Hydraulic)	Hydraulic	Lower cost, smaller size, higher stall torque, may stall without damage
Nacelle Structural Concept (Truss vs. Heavy Bed Beam vs. Semi-Monocque)	Truss Type	Approximately 1/2 cost of other concepts. Slightly less weight
Nacelle Truss Members (Closed Box vs. Open I Section)	Open I Sections	Best weld capability, least fabrication cost
Tower Configuration (Soft shell vs. Stiff Truss)	Soft Shell Tower (freq = 1.3 - 1.5 cycles/rev)	Soft Tower attenuates 2/rev loads. Lighter, cheaper. COE reduces 1¢/kWh
Tower Configuration (Soft vs Soft-Soft Tower)	Soft shell tower	The soft-soft shell (0.8 cycles/rev) resulted in small diameter (7 ft) tower. Not adequate for man-lift and no appreciable cost saving
Tower Configuration (Braced vs. Conical Base)	Conical Base (250 inch diameter)	Braced tower structurally indeterminate. Susceptable to differential settlement. Higher risk with no significant cost saving
Tower Configuration (Cone to Cylinder transition, abrupt vs. hyperbolic)	Hyperbolic Transition	Hyperbolic reduces local stresses and eliminates approx. 3600 lb of ring and gussets
Control System (Analog vs Microprocessor)	Microprocessor-based Digital System	Reliability due to less parts, reduced cost, commercially available components, flexibility to accommodate system changes, superior performance
Control System - Microprocessor Location (Ground vs. Nacelle)	Nacelle Computer and Signal Conditioning	The ground located system requires multiplexing system. Nacelle location provides COE reduction of 0.1¢/kWh

5.0 CONCLUSION

The MOD-2 wind turbine design, and the principal studies which developed this configuration have been summarized herein. The detailed discussion of all the activities accomplished during the Analysis and Design Phase are documented in Volume II of this report. Included in Volume II are the additional detailed discussions of:

- Structural analysis & code verification
- Control analysis and simulation results
- Performance analysis
- Weights analysis
- Safety, Reliability, Maintenance, and Logistics analysis
- Cost assessment
- Manufacturing development and test activities
- Manufacturing and Quality Assurance planning
- Transportation and Installation studies
- Test planning

The MOD-2 Project has successfully progressed with DOE/NASA approvals through the Conceptual Design Review (CDR) and the Preliminary Design Review (PDR). The experience gained from predecessor wind turbine programs has been infused by the NASA into this MOD-2 program. Several utilities and consultants have provided program guidance. A broad spectrum of industry fabricators, subsystem designers, equipment suppliers and construction firms have contributed valuable expertise in support of design and system costing.

These efforts have provided confidence that the MOD-2 Project will be able to realize the goals of cost of energy at less than 4¢/kWh and of early commercialization of wind energy.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR -159609		

4. Title and Subtitle MOD-2 Wind Turbine System Concept and Preliminary Design Report Volume I Executive Summary	5. Report Date July 1979 6. Performing Organization Code
7. Author(s) Boeing Engineering and Construction Company	8. Performing Organization Report No.
9. Performing Organization Name and Address Boeing Engineering and Construction Company (A Division of The Boeing Company) P.O. Box 3707 Seattle, Washington 98124	10. Work Unit No. 11. Contract or Grant No. DEN 3-2 13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address U.S. Department of Energy Distributed Solar Technology Division Washington, D.C. 20545	14. Sponsoring Agency ~~Code~~ Report No. DOE/NASA/0002-80/2

15. Supplementary Notes

Task completion report, prepared under Interagency Agreement DE-AI01-79ET 20305. NASA Project Manager, J. Couch, Lewis Research Center, Cleveland, Ohio 44135.

16. Abstract

Report of work performed during Task II Analysis and Design of Contract DEN 3-2. This report documents the configuration development of the MOD-2 Wind Turbine System. The MOD-2 WTS project is a continuation of DOE programs to develop and achieve early commercialization of wind energy. The MOD-2 is design optimized for commercial production rates which, in multi-unit installations, will be integrated into a utility power grid and achieve a cost of electricity at less than 4¢ per kilowatt hour.

This report is the Volume I Executive Summary. The full report includes Volume II Detailed Report.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Wind Turbine Electrical Power Non-expendable Energy Source Wind Energy	**Unclassified - unlimited** **STAR Category** 44 **DOE Category UC-** 60

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	**Unclassified**	27	

* For sale by the National Technical Information Service, Springfield, Virginia 22161